# 3D Metallic Photonic-Crystals and its Energy Consequences

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A review will be given on the recent development of 3D all-metallic photonic-crystals at the near-infrared and visible wavelengths. The energy consequences of the narrow-band emission will be described. Three specific examples are (1) the realization of efficient infrared light sources: (2) the material challenges and nanofabrication of photonic-crystals at near visible wavelengths; and (3) an efficient and portable electric power generation vusing long wavelength photo-voltaic (PV) cells.

In addition to achieving a narrow-band emission, we have recently developed photovoltaic cells using a new InGaSb material system. The InGaSb substrate has an electronic band gap at 2 to 5 μm and is suitable for low temperature (T<1,000K) Thermal PV operation. Secondly, by incorporating different metals onto a 3D photonic-crystal, we demonstrated a photonic band-edge at near visible wavelength. Experimental results from different metal coating, including Pt, Co and Cu, will be presented. Finally, a new growth technique for realizing 3D spiral photonic-crystals using glancing angle deposition method will be described.

# Thermal emission from an active metallic photonic crystal

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A quantum optics approach coupled with plane wave expansion and transfer matrix techniques is used to calculate the thermal emission from an active 3D metallic photonic crystal. The emitting source is modeled as a collection of inhomogenously broadened two-level systems that is allowed to equilibrate via collisions to a Maxwell-Boltzmann distribution at a specific temperature. Emission and absorption processes create a photon population within the photonic lattice as dictated by the photonic lattice bandstructure. This population is then coupled to the exterior to give the output of the active photonic crystal. The outcoupling of the intracavity radiation is investigated with different schemes: passive photonic filter, photonic crystal cavity coupler, and in terms of the modes of the 'universe'. A similar treatment of the blackbody is conducted and the results are compared to those of the photonic lattice. Discussions pertaining to the consistency of the results with the second law of thermodynamics are addressed.
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# Ultrafast Particle Plasmon Dynamics of Waveguide-Plasmon Polaritons

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The interaction between optical waveguide modes and particle plasmon resonances in so-called metallo-dielectric photonic crystal slab structures leads to strong coupling phenomena [1]. New collective states are formed which can be described by means of a polariton model (a so-called "waveguide-plasmon polariton"). This leads to a drastic modification of the optical response of the polaritonic system.

In the present work, the dephasing times of the polariton resonances in a two-dimensional metallo-dielectric photonic crystal slab structure are investigated. All measurements are based on a nonlinear interferometric autocorrelation technique which allows the measurement of the dephasing times in the time domain.

When tuning the waveguide mode to the particle plasmon resonances by an appropriate structuring of the photonic crystal period, the photonic density of states is strongly modified. The change in the density of states results in a reduced radiative decay and therefore a prolonged dephasing time of the waveguide-plasmon polariton compared to single particle plasmons. By fitting the measured autocorrelation traces with a simple damped oscillator model [2], we can extract a lower limit of the dephasing time of the appearing polariton branches. We found a dephasing time of $T_2$=30 fs which is nearly three times as long as the uncoupled particle plasmon dephasing time [3].

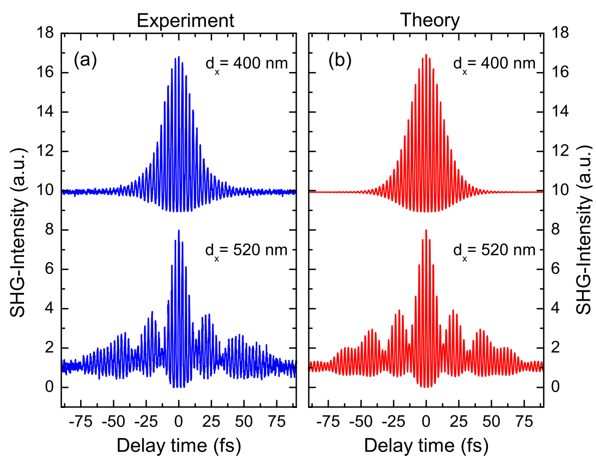


Fig. 1: Measured (a) and calculated (b) second-order autocorrelation signal of a 13 fs laser pulse interacting with the metallic photonic crystal slab for two photonic crystal periods.

In conclusion, we have demonstrated experimentally that the dephasing time of the coherent excitation of particle plasmons can be tailored by an appropriate structuring of the photonic crystal period in metallic photonic crystal structures.

[1] A. Christ *et al.*, Phys. Rev. B **70**, 125113 (2004).
[2] B. Lamprecht *et al.*, Phys. Rev. Lett. **83**, 4421 (1999).
[3] T. Zentgraf *et al.*, Phys. Rev. Lett. **93**, 243901 (2004)

# Modifying the properties of plasmonic crystals through engineering of the primitive unit cell

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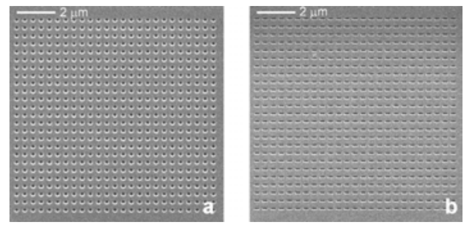
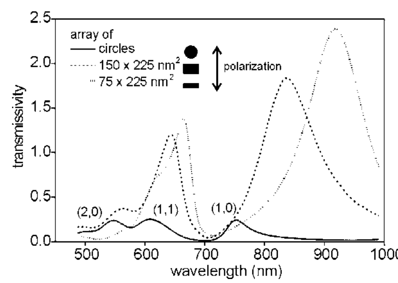
Extraordinary transmission, first observed by Ebbesen and co-workers, is one of the most beautiful phenomena in plasmonic crystals. This transmission has generally been attributed to a resonant excitation of surface plasmons set up by the periodicity of the array. *Here, we will show that this explanation cannot be the entire story.*

Contrary to expectations, by changing the shape of the sub-wavelength holes and thus engineering the primitive unit cell, we are able to enhance and, more importantly, change the peak positions.




[1] K.J. Klein Koerkamp, et al., *Phys. Rev. Lett.* **92**, 183901 (2004). [2] K.L. van der Molen, et al., *Appl. Phys. Lett.* **85**, 4316 (2004).

# New photonic structures in biology

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Many living organisms have developed complex photonic structures which work at filtering visible and near-visible light, providing these species with natural competing advantages in their developing environment. The iridescent colors of some insects (butterfly, beetles, weevils, dragonflies…) and the colored reflections from bird feathers are well-known examples of these.

In this communication, we discuss some recent progress in the understanding of the structures, and of the functions of these structures, found on highly evolved organisms. On the basis of investigations recently carried out in Namur [1], we show that (1) photonic structures can have important impact on the thermal stability of living species in rough environment (example of the butterfly *Polyommatus daphnis*), (2) light manipulation by photonic structure can lead to non-iridescent colors (example of the butterfly *Cyanophrys remus*, which shows photonic "polycristalline" structures), (3) photonic structures can efficiently protect against ultraviolet radiation (example of the "edelweiss", *Leontopodium nivale*, fleece submicron structure).

Issues regarding the numerical simulation of the complex structures showing up in biology will be addressed and the impact of such studies on the design of artificial structures will be discussed.

[1] L.P. Biró *et al.*, Phys. Rev. E **67**, 021907 (2003); J.P. Vigneron et al. Phys. Rev. E **71**, 011906 (2005)

# Light-emitting biological photonic crystals

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Photonic crystal structures in nature are extremely diverse with respect to material composition, structural complexity and function. Here we present one of the few examples of photonic crystals in plants that offers the possibility of tailoring the material composite properties. The silica cell wall of centric diatoms (genus *Coscinodiscus*) can be regarded as photonic crystal slab waveguide with hexagonal and square patterns (Fig. 1, Ref. [1]). The biological process of silica deposition allows the incorporation of certain dyes into the biocomposite structure by *in-vivo* techniques. Experiments on the incorporation of laser dyes and their emission properties in the slab waveguide structure are presented.

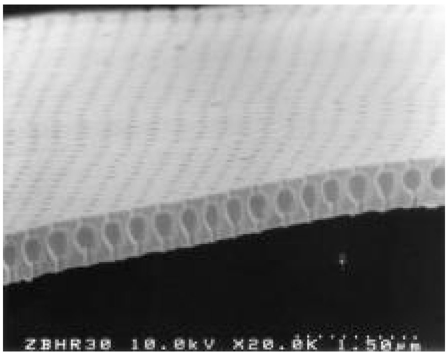

Fig. 1 Cell wall of *C. wailesii*

[1] T. Fuhrmann, S. Landwehr, M. El Rharbi-Kucki, M. Sumper, *Appl. Phys. B*, **78**, 257 (2004).

**Optically-induced photonic lattices:**
**an analog of nonlinear photonic crystals**

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We present an up-to-date overview of both theoretical and experimental results on the physics of one- and two-dimensional nonlinear photonic lattices induced optically in photorefractive crystals. Such optically-induced linear and nonlinear photonic lattices provide an ideal test-bed for demonstrating many novel nonlinear phenomena in photonic periodic structures, due to their dynamical tunability and strong nonlinear effects that can be observed at moderate laser powers, thus studying the basic properties of nonlinear photonic crystals as building blocks for future all-optical switching technologies. Using these optically-induced lattices, we were able to observe experimentally both linear and nonlinear Bragg scattering [1], the formation of optical spatially localized structures in the form of self-trapped lattice solitons and spatial gap solitons [2] creating by self-focusing of Bloch waves, as well as novel types of optical vortices in lattices [3]. We have also generated multi-gap states belonging to different spectral gaps. We have demonstrated interaction and steering of gap solitons, which are the key features for a new type of light controlling devices based on periodic photonic structures, including nonlinear photonic crystals.

[1] A.A. Sukhorukov, D. Neshev, W. Krolikowski, and Yu.S. Kivshar, Phys. Rev. Lett. **92**, 093901(4) (2004)
[2] D. Neshev, A. A. Sukhorukov, B. Hanna, W. Krolikowski, and Yu. S. Kivshar, Phys. Rev. Lett. **93**, 083905(4) (2004).
[3] D. Neshev, T. J. Alexander, E. A. Ostrovskaya, Yu. S. Kivshar, H. Martin, I. Makasyuk, and Z. Chen, Phys. Rev. Lett. **92**, 123903 (2004).